EXAMINED AND ANALYSIS OF EMPIRICAL SEISMIC DAMAGE OF WORKSHOP BUILDING

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ABSTRACT

To deeply explore the typical damage characteristics and vulnerability characteristics of workshop buildings (WBs) in actual earthquakes, empirical field reconnaissance and observation of WBs damaged to varying degrees in the Mw 8.0 earthquake in Wenchuan County, Sichuan Province, China, on May 12, 2008, were conducted. The investigation results indicated that the typical seismic damage forms of industrial buildings in multiple intensity regions were: local and overall collapse, column cracking and crane beam displacement, failure and cracking of walls, and damage of supporting and connecting members. Field investigation pictures of typical seismic damage were provided. According to different typical failure characteristics, the seismic damage mechanism and seismic capacity were analysed, and measures and suggestions to improve the seismic ability of industrial buildings with different material categories were conducted. The conclusions can provide a necessary reference for the revision of the seismic code of industrial plants and the seismic intensity scale of China.

KEYWORDS

Workshop Building, Empirical Seismic Damage Observation, Analysis of Typical Failure Characteristics, Failure Analysis, Seismic Damage of Components

INTRODUCTION

Earthquakes of different intensities significantly impact the natural environment and infrastructure, which will commonly cause traffic blocking and buildings stock failure [1], especially damage to artificial structures. A large amount of empirical seismic damage observation data indicates that many casualties and property losses are caused by the failure or serious damage of engineering structures. Therefore, to improve the ability of structures to resist earthquakes of different intensities, deeply studying the seismic capacity and vulnerability characteristics of engineering structures has critical engineering and practical significance.

Empirical structural seismic damage investigation and vibration model analysis can effectively evaluate the seismic damage of building structures under different intensity levels. Sun et al. [2] and Qu et al. [3] conducted damage analysis and statistics on the seismic damage investigation data of structures (reinforced concrete structure (RC), masonry structure (MS), and wood structure) in the Lushan earthquake in China, and empirical seismic vulnerability analysis considering this earthquake was provided. Li et al. [4-8] investigated and analysed the actual seismic damage of MS, RC, and bottom frame seismic wall masonry structures (BFSWMSs) damaged to varying degrees in the Wenchuan earthquake in China, compared the vulnerability in combination with a variety of coupling influence factors, and established an empirical seismic damage vulnerability probability demand model considering multiple intensity regions. Bagheri et al. [9] and Miglietta et al. [10] conducted an experimental study on the structural model under a strong medium earthquake considering the structural seismic response system, and the relationship model between impact and floor ductility high-rise structures under specific ground motions was analysed.

With the gradual development of factory manufacturing, WB has been extensively used in different regions. This type of structure has the characteristics of a large bay, flexible spatial layout, and strong applicability and is especially suitable for the production and manufacture of large objects. However, owing to the seismic action of different intensity levels, WB has suffered many degrees of earthquake damage, which has seriously affected industrial production and even threatened people’s life safety and property loss. Palanci et al. [11] investigated single-story prefabricated industrial buildings in Turkey using probability and statistics methods, conducted inelastic and time history analysis combined with typical WB and produced a vulnerability curve model considering the ground peak acceleration parameter. A two-level fuzzy comprehensive evaluation method was proposed by Sun and Zhang [12], which can be used for seismic damage assessment and risk analysis of single-layer reinforced concrete industrial plants. Casotto et al. [13] analysed the vulnerability model of RC prefabricated industrial buildings that suffered typical damage in northern Italy, conducted regression analysis considering the cumulative percentage parameters of different failure states, and obtained the vulnerability function model under the influence of varying strength modulus. Wang et al. [14] utilized ABAQUS analysis software to establish a finite element model of a single-layer brick column factory building and performed dynamic response and failure mechanism analysis.

The relevant research mentioned above mainly focuses on the empirical seismic damage investigation and model analysis of a single WB, such as damage investigation of a single structure, 3D finite element model, and shaking table test. It has achieved a great deal of scientific research results. However, by analysing the failure characteristics of a single typical WB, it is difficult to effectively grasp the typical seismic damage characteristics of WB in the overall seismic region to a certain extent. Therefore, to effectively grasp the typical seismic damage characteristics of WB structures, based on the empirical structural seismic damage observation data of the Wenchuan Mw 8.0 earthquake on May 12, 2008 [4-8], this study analyses and summarizes the typical damage characteristics of WB in the overall survey region and puts forward measures and methods to effectively improve the seismic capacity of WB according to different damage characteristics.

BRIEF INTRODUCTION OF STRUCTURAL DAMAGE INVESTIGATION IN WENCHUAN EARTHQUAKE

On May 12, 2008, a magnitude 8.0 earthquake occurred in Wenchuan County, Sichuan Province, China, causing a large number of casualties and property losses. After the earthquake, the China Earthquake Administration quickly organized a field seismic damage reconnaissance team to investigate structural seismic damage on various structures in 33 cities and villages [5] [7]. The author and relevant personnel of the investigation team participated in the investigation. They carried out a field actual seismic damage investigation on 18480 building structures in different intensity regions according to the seismic intensity distribution map (as reported in Figure 1 [15], China seismic code (GBJ11-89, GB50011-2001, and GB50011-2010) [16][17][18], and China seismic intensity scale (GB/T17742-2020, CSIS-20) [19], including all building samples (7099 buildings) investigated in Dujiangyan city. The structural categories investigated in the earthquake region are diversified. Table 1 summarizes the main categories of building structures in the investigated region.

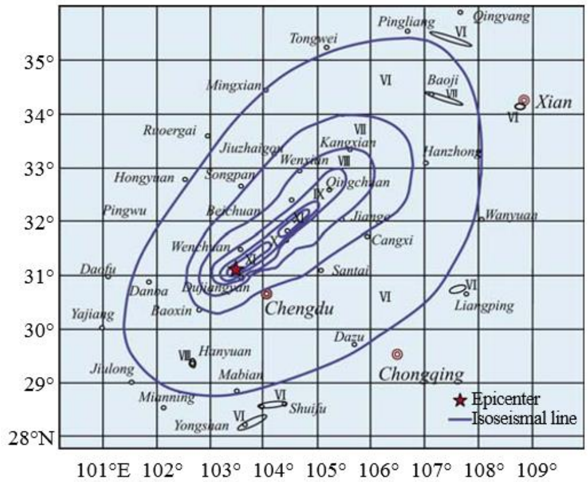

Fig. - 1 Macrointensity map of Wenchuan earthquake in China [5][15]

Tab. 1 - Type of structure investigated in the actual earthquake region

Category	WB	Other
	Masonry industrial building, single-story concrete of workshop, the single-story steel frame of the workshop, single (multiple) story RC of industrial workshop, RC industrial plant with masonry infilled wall, single-story masonry industrial plant	RC, MS, BFM, Brick wood structure, and adobe structure

According to the field seismic damage investigation of various structures, the WB of the steel frame is less damaged in different intensity regions, and a certain number of masonry WB are subjected to different degrees of seismic damage. The damage to the RC structure is relatively light, the MS after seismic design shows good seismic performance, and the deterioration of the BFM is relatively heavy due to the inconsistency of the structural stress system. The damage to brick wood and adobe structures is relatively significant. It is worth noting that WB structure types show diversified characteristics, and the seismic damage is more significant in different intensity areas. To relatively accurately and comprehensively grasp the typical damage characteristics of this type of structure, the investigation and analysis of typical seismic damage of WB should be considered.

ANALYSIS OF EMPIRICAL SEISMIC DAMAGE CHARACTERISTICS OF WB

With the rapid and sustainable development of the global industry and manufacturing industry, the demand for industrial plant buildings (WBs) in various industries has increased significantly. Single-story industrial plant buildings are the main structural form of plant buildings in different industrial areas in China. The investigation data of the empirical seismic damage of the Wenchuan earthquake indicated that WB built with different materials suffered various degrees of seismic damage and caused substantial economic losses. The field structural seismic damage reconnaissance team investigated and analysed the seismic damage of the overall and local components of WB in multiple intensity regions. The damage forms mainly include local and overall structural failure, column cracking and crane beam displacement, wall failure and cracking failure, and seismic damage of support and connecting components. The structural form and category is divided into reinforced concrete bent column workshop, steel structure workshop, brick column workshop, frame bent workshop, and steel-concrete composite structure workshop. This study analyses the failure characteristics and mechanisms according to the empirical seismic damage and types mentioned above.

Local or overall structural failure

The investigation team found that in the high-intensity area, due to the relatively weak stiffness and strength at the connection between the precast beam and column, the beam was seriously displaced or even fell under the reciprocating action of ground motion, resulting in local collapse. In addition, individual brick plants experience an overall collapse in the multi-intensity region, owing to their brittle materials and weak vertical and horizontal constraints, as depicted in Figure 2. It should be considered to properly strengthen the connection between the crane beam and corbel, improve the integrity of longitudinal and transverse stressed members, and reasonably set diagonal bracing members to enhance lateral stiffness to coordinate the overall deformation of the structure. Structural members composed of multiple materials should be avoided, the lateral force resistance of the structure should be reasonably increased, and the seismic effect of the structure should be inproved.

(a) Local collapse of RC industrial building

(b) Collapse of MS industrial building

(c) Failure of steel structure industrial building

(d) Failure of roof slabs and beams in an industrial building

(e) Overall failure of MS and steel frame industrial building

(f) Failure of upper transverse beam and plate of industrial building

Fig. 2 - Overall and local failure of WB

Column cracking and crane beam displacement

The seismic damage of the WB column was typical in the investigation work. The failure forms were: oblique and transverse cracking of the column (column head, column body, and column base), cracking of the concrete corbel root, cracking at the variable section, and cracking at the column beam joint, as illustrated in Figure 3. Owing to the column ends (top and bottom) being generally subjected to large horizontal earthquakes, a the large shear force was generated and led to shear failure. The failure of the column body was characterized by transverse cracking, local compression, and crisp crushing, resulting in a short column effect, and cracking failure was caused by the coupling effect of bending and tension. Shear or crushing cracking often occurs at the variable section of the concrete column (corbel). Because this position was at the variable section of the column, it caused sudden changes in stress and force transmission coupled with insufficient strength and stiffness, resulting in cracking failure.

(a) Cracking failure of the RC column head

(b) Oblique cracking failure of RC frame column

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(c) Transverse cracking failure of the brick column

(d) Cracking failure of the lower part of the brick column

(e) Cracking and failure of corbel root

(f) Crushing cracking failure of corbel end

(g) Longitudinal displacement of crane beam

(h) Vertical cracking failure of crane beam

Fig. 3 - Seismic damage of columns and crane beams

In addition, it was found in the investigation that some column and beam joints produce plastic hinges and crack damage. Individual crane beams cause the corresponding displacement due to insufficient longitudinal restraint. The columns of different materials should be checked in strict accordance with the seismic design requirements to ensure that they have sufficient seismic capacity. Reasonably improve the ductility to reach the plastic state and still have a certain bearing capacity and deformation capacity when working. Properly control the section shape of a variable column and the ratio of the section area and linear stiffness of the upper and lower columns. The corbel should be subjected to strict seismic checking calculations of stiffness, strength, and ductility, and the lateral stiffness should be reasonably designed to avoid the increase in seismic force caused by too short a transverse period due to improper design.

Cracking and failure of the wall

Walls are a vital enclosure component of WB, which can avoid the adverse impact of natural environmental factors on the structural system, ensure the normal use of WB, and play the role of enclosure and blocking space. According to the field investigation of empirical seismic damage, most of the retaining walls are self-supporting brick walls, with relatively small shear and bending resistance and insufficient seismic capacity. Under the reciprocating action of longitudinal ground motion, it is easy to produce a "whiplash effect," resulting in outward inclination of the top and local or overall collapse, as demonstrated in Figure 4.

(a) Failure of Maintenance wall (gable)

(b) Local collapse of building a wall of RC bent workshop

(c) Overall wall failure of maintenance wall

(d) Local collapse of maintenance wall

(e) Collapse of upper maintenance wall *(f) Partial failure of upper maintenance wall*

Fig. 4 - Seismic damage of maintenance wall

In the low and medium-intensity regions, some walls show transverse and oblique cracking failure, especially at the door and window openings caused by stress concentrations, as depicted in Figure 5.

(a) Cracking of wall between windows *(b) Oblique cracking of wall*

(c) Cracking of inner wall *(d) Cracking and damage at the door opening*

Fig. 5 - Crack and damage of maintenance wall

WB's stress system is a bent or frame structure system. The maintenance wall is a nonstructural member. It first fails with beams and columns, which protects the bearing capacity of the main structure to a certain extent, plays the role of "the first line of defense," and has positive seismic significance. The necessary design should be conducted in strict accordance with the code for seismic design of building structures, the essential description of the wall structure design, the seismic checking calculation of tie joints, the connection between the wall and structural members should be strengthened to coordinate its stiffness and mass distribution, and the seismic performance of the wall should be further included in the seismic checking calculation of WB.

Seismic damage of supporting and connecting members

The practical setting of X-type and horizontal support and connection can improve the lateral stiffness of WB to a certain extent to improve its seismic performance. In the field seismic damage investigation, it is found that the yield of supporting and connecting members is relatively significant. When subjected to an earthquake, the roof truss and roof system produce a large horizontal inertial force, resulting in more considerable pressure and tension on the support members. In addition, the support system suffers buckling or failure due to insufficient stiffness and connection strength, as depicted in Figure 6.

It is necessary to consider the essential aseismic checking of the X-type supporting system and appropriately increase its stiffness and lateral force resistance. Strengthen the joint strength between the vertical and horizontal connecting members and the main structure to have the same deformation coordination ability. However, the buckling or failure of the X-brace consumes part of the seismic capacity to a certain extent and has a certain protective effect on the main structural system.

(a) Buckling of X-brace

(b) Failure of horizontal contact

Fig. 6 - Seismic damage of supporting and connecting members

Basically intact

During the field investigation, it was found that a large amount of light steel structure WB and constrained brick WB after seismic design were basically intact, as illustrated in Figure 7. It is worth noting that even in the high-intensity regions, a certain number of light steel structures WB and brick WB after seismic design were still undamaged.

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(a) Light steel workshop

(b) Steel structure workshop

(c) Steel frame workshop

(d) Brick workshop with seismic design

Fig. 7 - Basically intact of WB

The main reason was that the light steel structure has a strong overall deformation capacity, light material texture, and relatively small inertial force. After the seismic design, the brick WB has the seismic structural measures of ring beam and connecting column so that its seismic capacity can be further improved. In new construction or reinforcement projects, priority should be provided to the use of light steel structure WB and brick WB structure category with seismic design to ensure that the structural design and construction are performed in strict accordance with the seismic code.

CONCLUSION

WB structures have attracted much attention as a widely used structure type worldwide. This type of structure has suffered many degrees of seismic damage in different levels of earthquakes, which directly affects human safety and property damage. In this study, employing the WB damage of the empirical seismic damage investigation of the Wenchuan earthquake on May 12, 2008, in China as the research case, the damage characteristics and mechanism analysis are performed for the local or overall failure of the structure, the damage of columns and crane beams, the seismic damage of retaining walls and the damage of supports and connections. The following opinions and suggestions are obtained:

1. It should be considered to prioritize the selection of light steel structure roof systems in different intensity regions, reasonably reduce the self-weight of the structure, reduce the support system, and avoid the failure of connecting structure and load-bearing structural components.

2. Reasonably strengthen the structural connection of local joints to ensure the connection strength and stiffness of the corbel and roof truss system. A light steel structure plate should be considered for skylight frames.

3. A steel structure or RC column should be preferentially selected as the vertical stress system for the single-story plant to reasonably ensure the ductility of the components. Ensure that the lateral stiffness of the column is suitable for the section size and avoid the increase in seismic force caused by the shortening of the structural period.

4. Priority should be given to the use of lightweight precast wallboards as enclosure structures. In strict accordance with the seismic code, the effective connection between the retaining wall and the column and beam is strengthen, and the integrity of the structure is improved.

5. It is suggested to use X-braced steel members with relatively good energy dissipation and deformation capacity to improve the lateral force resistance of WB and the seismic resistance of the whole structure.

The results of this study can provide necessary references for the empirical seismic damage investigation and evaluation of WB structures, the revision of seismic codes, and seismic intensity scales in the future.

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